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Calibration of the Horizontal Receive Array of the Experimental Array Radar System

Alan D. Thomson and Edwin S. Riseborough
Defence Research Establishment Ottawa

Defence R&D Canada

DEFENCE RESEARCH ESTABLISHMENT OTTAWA

TECHNICAL MEMORANDUM
DREO TM 2000-060
November 2000

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Surface Radar Section

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Abstract

Calibration coefficients have been calculated for the horizontal receive array of the Experimental Array Radar System (EARS). These coefficients scale the power produced at the output of a receive channel to the power expected based on physical considerations. In total 96 coefficients have been calculated for the 8 antenna horns and their respective receive channels. Each horn/channel was calibrated for 12 transmitted waveforms corresponding to the different combinations of 6 frequencies and 2 pulse widths. The method of calibration is described using the example case of antenna horn 4 (receive channel 12), a transmitted frequency of 9.0 GHz, and a pulse width of 1.0 μs. Calibrated data corresponding to this case were required to evaluate a high fidelity radar weather clutter simulation developed at the Defence Research Establishment Ottawa (DREO). The accuracy of the example calibration coefficient (1.79×10^{-2}) was evaluated by comparing the reflectivity factor and rain rate derived from EARS measurements of precipitation with similar values derived from simultaneous measurements made by a Joss-Waldvogel disdrometer. The results of the comparison indicated that the horizontal receive array of EARS has been effectively calibrated.

Résumé

Les coefficients de calibration ont été calculés pour le réseau récepteur horizontal du système radar expérimental à réseau d'antenne (EARS). Ces coefficients échelonnent la puissance produite à la sortie du canal récepteur en fonction de la puissance prédite des considérations physiques. Au total 96 coefficients ont été calculés pour les 8 antennes cornets et leur canal récepteurs respectif. Chaque cornet/canal a été calibré pour douze formes d'onde correspondant aux différentes combinaisons des 6 fréquences et de deux durées d'impulsion. La méthode de calibration est décrite en utilisant l'exemple du cas de 4 antennes cornets (canal de réception 12), une fréquence de transmission de 9 GHz, et une durée d'impulsion de une micro seconde. Les données calibrées correspondant à ce cas étaient requises pour évaluer une simulation haute-fidélité de fouillis radar météorologique développée par le Centre de Recherches de la Défense d'Ottawa. La précision de nos coefficients de calibration (1.79×10^{-2}) a été évaluée en comparant le pouvoir réflecteur et le taux de pluie obtenu a partir de mesures de précipitation obtenu avec le système radar EARS et de mesures simultanées prises par un disdromètre Joss-Waldvogel. Les résultats de la comparaison indiquent que le réseau récepteur horizontal du système radar EARS a été calibré de façon efficace.

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Executive summary

The Experimental Array Radar System (EARS) is an X-band pulsed Doppler radar. The main role of EARS has been to collect data for studies related to shipborne radar applications. In particular, EARS data have been used for low-angle tracking studies and to test adaptive nulling techniques designed to counter hostile electronic counter measures employed by stand-off and self-protection jammers. EARS has also been used to collect high-range resolution signatures for non-cooperative target recognition studies. In addition, EARS has been used to provide a source of sea and weather clutter data.

Field trials, involving EARS, have been conducted to provide a data set for testing the accuracy and capabilities of a high fidelity radar weather clutter simulation developed at DREO. This simulation was created to produce a controllable source of weather clutter data that can be used to develop and test detection algorithms designed to perform well in an environment containing precipitation. Data produced by the simulation were compared with the real data measured by EARS as a means of evaluating the accuracy of the weather clutter simulation. This comparison required the EARS data to be properly calibrated.

This report documents how the horizontal receive array of EARS was calibrated. The accuracy of the calculated calibration coefficient corresponding to a particular antenna horn and receive channel of the array is also evaluated by comparing quantities derived from the calibrated EARS data with similar quantities determined from simultaneous measurements made by an independent collocated instrument.

A favourable comparison was achieved between the quantities derived from the two instruments. This indicated that the EARS calibration coefficient was accurate and that the horizontal array has been effectively calibrated.

Thomson, A. D., and Riseborough, E. S., 2000. Calibration of the Horizontal Receive Array of the Experimental Array Radar System. TM 2000-060, Defence Research Establishment Ottawa.

Sommaire

Le système radar expérimental à réseau d'antenne (EARS) est un radar Doppler à impulsion dans la bande X. Le rôle principal de EARS est de collectionné des données pour des études reliées aux applications de radar naval. En particulier, les données de EARS ont été utilisées pour des études de poursuite à faible angle d'incidence et pour tester des techniques d'adaptation de creux d'antennes pour contrer des contre-mesures électroniques hostiles employées par des brouilleurs à distance de sécurité et d'autodéfense. EARS est aussi utilisée pour collecter des signatures haute-résolution en portée pour des études de fonction de détection "non coopérative. En addition, EARS a été utilisé comme une source de données radar de fouillis météorologique et d'écho de vagues.

Des essais pratiques, impliquant EARS, ont été effectués pour obtenir un ensemble de données radar pour tester la précision et la capacité de la simulation haute-fidélité de fouillis radar météorologique développée au CRDO. Cette simulation a été créée pour produire une source contrôlable de fouillis radar météorologique qui peut être utiliser pour développer et tester des algorithmes de détection dans un environnement contenant des précipitations. Les données produite par le simulateur ont été comparées avec des données radar réelles mesurées par le système EARS comme un moyen d'évaluer la précision de la simulation du fouillis radar météorologique. Cette comparaison exige que les données du système EARS soit bien calibrer.

Ce rapport documente comment le réseau de réception horizontal EARS a été calibrée. La précision des coefficients de calibration calculée correspondant à une antenne cornet et un canal récepteur particulier du réseau d'antenne est aussi évaluée en comparant les quantités obtenues des données calibrées de EARS avec des quantités similaires déterminé de mesures simultanées prisent avec un instrument indépendant co-implantée.

Une comparaison favorable est obtenue entre les quantités dérivées des deux instruments. Ceci indique que les coefficients de calibration du système EARS sont précis et que le réseau horizontal a été calibré de façon efficace.

Thomson, A. D., and Riseborough, E. S., 2000. Calibration of the Horizontal Receive Array of the Experimental Array Radar System. TM 2000-060, Defence Research Establishment Ottawa.

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1 Introduction

The Experimental Array Radar System (EARS) is an X-band pulsed Doppler radar. The main role of EARS has been to collect data for studies related to shipborne radar applications. In particular, EARS data have been used for low-angle tracking studies and to test adaptive nulling techniques designed to counter hostile electronic counter measures employed by stand-off and self-protection jammers. EARS has also been used to collect high-range resolution signatures for non-cooperative target recognition studies. In addition, EARS has been used to provide a source of sea and weather clutter data.

Field trials, involving EARS, were conducted during June 18-22, 1997 to provide a data set for testing the accuracy and capabilities of a high fidelity radar weather clutter simulation developed at DREO (Thomson [1]; Thomson and Riseborough [2]). The simulation was created to produce a controllable source of weather clutter data that can be used to develop and test detection algorithms designed to perform well in an environment containing precipitation. Data produced by the simulation were compared with the real data measured by antenna horn 4 (channel 12) of the EARS horizontal receive array. This comparison required a properly calibrated EARS data set of in-phase and quadrature signal samples.

This report describes how the calibration coefficients that properly scale the mean power represented by the in-phase and quadrature signal samples measured by EARS are determined. Each of the 8 antenna horns and receive channels of the EARS horizontal array are calibrated for 12 transmitted waveforms corresponding to the different combinations of 6 frequencies and 2 pulse widths. The resulting 96 coefficients are tabulated in this report for future reference. The method of calibration is described with an example calculation corresponding to the EARS data measured during the weather clutter field trials with horn 4 and channel 12. The accuracy of the example calibration coefficient is also evaluated by comparing the reflectivity factor and rain rate values derived from the calibrated EARS data with those determined from simultaneous measurements made by a collocated Joss-Waldvogel disdrometer. In addition, the reflectivity factor data of both these instruments are compared with the measurements made by the Environment Canada weather radar at Carp, Ontario.

2 Calibration

2.1 Experimental measurements

EARS (Riseborough [3]) was located at a DREO site on the shore of the Ottawa River for both the calibration measurements (March 12, 1997) and the weather clutter field trials (see Figure 1). At this location EARS was used to emulate a shipborne horizon search radar by making measurements along horizontal rays over the river. A photograph of EARS is shown in Figure 2.

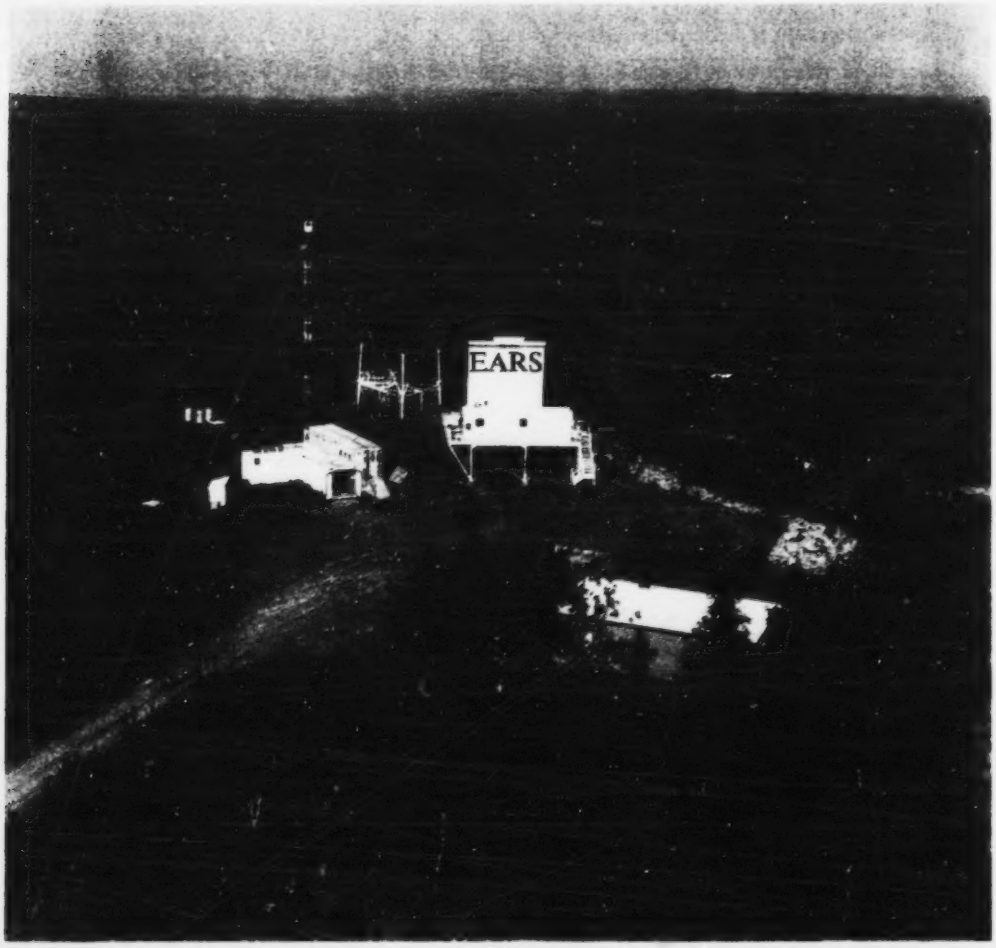

Figure 1. *EARS view along a 14 km expanse of the Ottawa River. EARS is located inside the building marked "EARS" and looks in the direction of the photograph.*

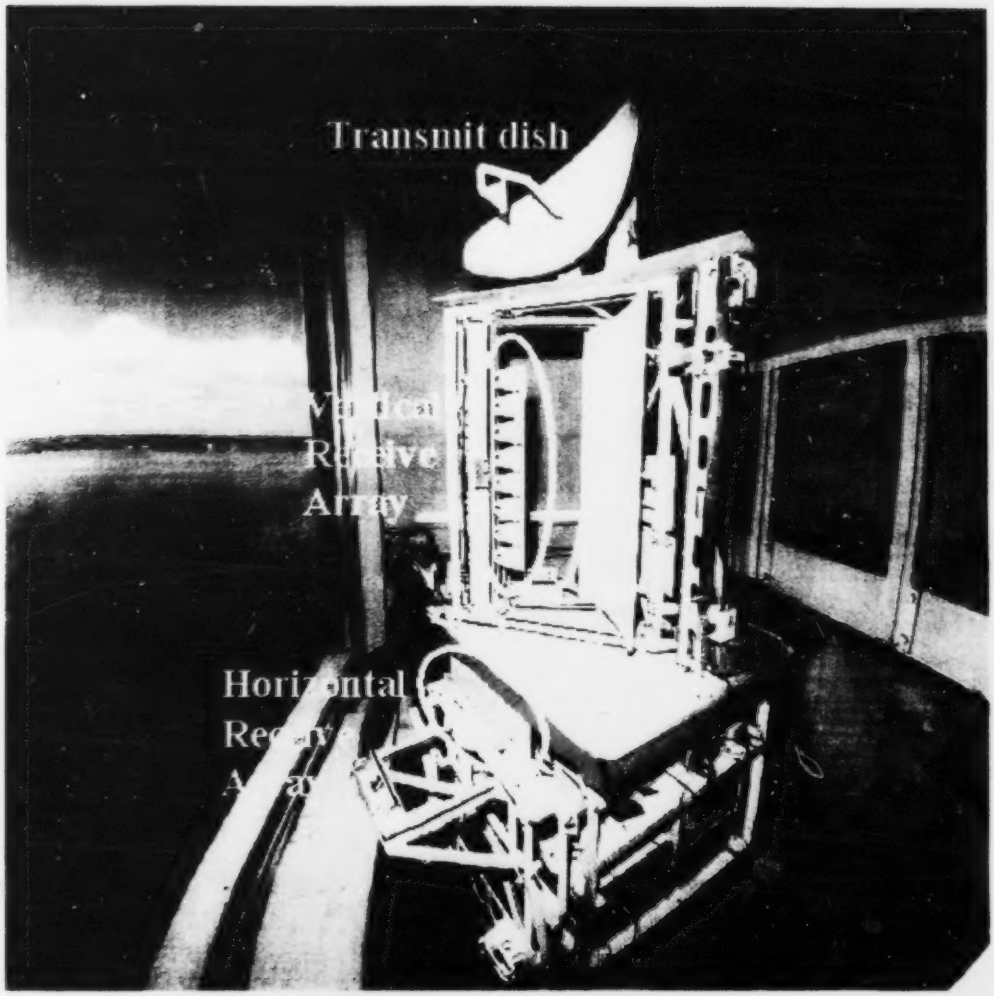

Figure 2. *Experimental Array Radar System (EARS).*

EARS uses an elliptical parabolic dish for the transmitting antenna and two arrays of NARDA 640 standard gain horns as the receiving antenna. The simulated weather clutter data were compared only with the measurements made using horn 4 and the corresponding receive channel, 12, of the horizontal array. Thus, the method, and the evaluation, of the calibration will be discussed using horn 4 and channel 12 as an example.

The calibration coefficients corresponding to all horns are dependent upon the transmitted frequency and pulse width. The specific parameters used for both the calibration measurements corresponding to the example case and for the specific weather clutter measurements that were compared with simulated weather clutter are shown in Table 1.

Table 1. Parameters describing the EARS waveform used for calibration and weather clutter measurements.

SYMBOL	VALUE	DESCRIPTION
h_a	10.0 m	antenna system height above sea level
θ_b	8.27°	antenna system 6 dB elevation beamwidth
ϕ_b	3.66°	antenna system 6 dB azimuth beamwidth
G_b	23.9 dB	antenna system gain on the beam axis
P_t	68.5 dBm	transmitted power
f_t	9.0 GHz	transmitted frequency
Θ	0.0 (horizontal)	polarization
n_c	128	number of pulses in a coherent burst
T_s	1 ms	pulse repetition interval (calibration)
T_s	500 μs	pulse repetition interval (weather clutter)
τ	1.0 μs	pulse width
G_{sys}	84.2 dB	receiver system gain
B_6	5.0 MHz	6 dB receiver bandwidth
θ	0.0°	elevation of measurement ray
ϕ	329°	azimuth of measurement ray

A diagram of the experimental set-up used to collect the calibration data is shown in Figure 3. A trihedral corner reflector, characterized by a length $\ell = 0.493$ m (see Figure 4), was placed 3 m above the snow-covered frozen Ottawa River at a range of approximately 7.95 km. The azimuth alignment of the EARS antenna toward the corner reflector was set using a telescope. The orientation of the corner reflector was adjusted to provide the maximum returned signal strength.

2.2 Calculation of the Calibration coefficient

The calibration coefficient, ω, is the constant of proportionality that relates the expected power at the output of the EARS receiver to the power contained in the I and Q time series that are actually produced by the receiver. That is, the constant, ω, is determined such that it satisfies the following equation:

$$P_{expected} = \frac{P_t G_b^2 \lambda^2 G_{sys} \sigma}{(4\pi)^3 r^4} = \frac{\omega}{n_c} \sum_{n=0}^{n_c-1} \left(I_n^2 + Q_n^2\right) = \omega \left(\overline{I^2 + Q^2}\right) \qquad (1)$$

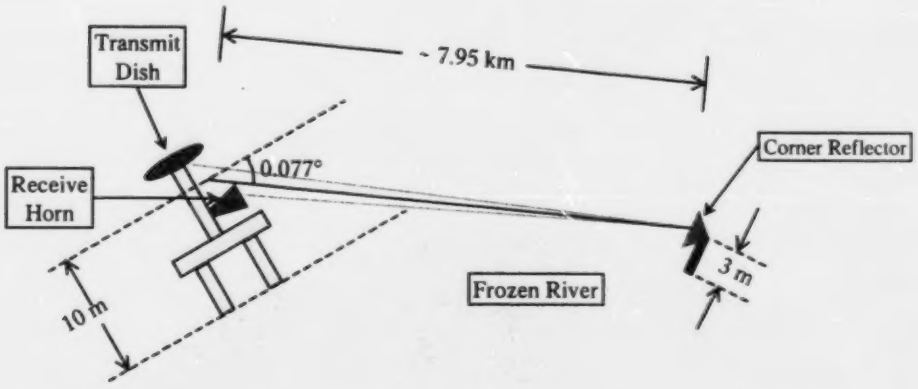

Figure 3. *Diagram of the experimental set-up used for the EARS calibration measurements. The angle 0.077° is based upon a ⅓ earth radius, which corresponds to propagation conditions in a "standard" atmosphere. The diagram is not drawn to scale.*

where P_t is the transmitted power, G_b is the antenna system gain on the beam axis, λ is the transmitted wavelength, G_{sys} is the receiver system gain, r is the range to the calibration target, σ is the backscatter cross section of the calibration target, n_c is the number of pulses transmitted by the radar, and I_n and Q_n are the uncalibrated signal samples measured by the radar. The backscatter cross section of the calibration target (corner reflector) is given by

$$\sigma = \frac{4\pi A_e^2}{\lambda^2} = \frac{3\pi \ell^4}{\lambda^2} \tag{2}$$

where A_e^2 is the effective area of the aperture (see Ruck et al. [4], p. 588). In this case

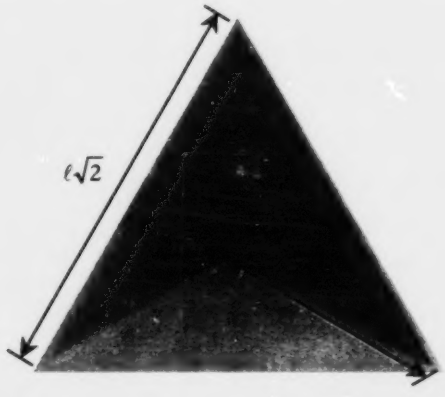

Figure 4. *Trihedral corner reflector having inner length ℓ.*

$A_c^2 = 0.75\ell^4$ since the incident beam axis is assumed to be normal to the surface defining the aperture of the corner reflector.

Assuming a system resistance of 1 Ω, the mean uncalibrated power measured by channel 12 of EARS, $\overline{I^2 + Q^2} = 0.4356$ W, was determined from 3700 I and Q samples measured over a period of 3.7 s. Using this value and the parameters of Table 1 in Eqs. (1) and (2) gives $\omega = 1.79 \times 10^{-2}$ (horn 4, channel 12, $f_t = 9.0$ GHz, $\tau = 1.0$ μs).

The calibration coefficients corresponding to all horns, transmitted frequencies, and pulse widths are shown in Tables 2 and 3. In each case, the required $\overline{I^2 + Q^2}$ values (see Tables 4 and 5) were again calculated using 3700 I and Q samples. The parameters of Table 1, except for the frequency and pulse width, apply to all values in Tables 2, 3, 4, and 5.

2.3 Error due to uncertainty in the target position

Equation (1) implicitly assumes that the calibration target is positioned at the centre of the radar resolution volume where it will receive the maximum weight applied by the antenna system. However, this was not the case for the actual measurements. As shown in Figure 3, the centre of the antenna system (transmit dish and receive horn) was positioned approximately 10 m above the ice surface. Thus, assuming propagation conditions corresponding to a "standard" atmosphere (4/3 earth radius), the corner reflector was 0.077° in elevation below the peak of the antenna system gain pattern. The actual elevation position of the corner reflector with respect to the antenna system gain pattern will depend on the specific propagation conditions that were present during the measurements.

The exact range of the corner reflector was also not known. However, EARS made measurements at many range bins along the ray through the corner reflector. The distance between the centres of adjacent range bins was 15 m and the pulse width, τ, was 1 μs. Significant returns were measured at all bins from 7.89 to 8.01 km. If the receiver bandwidth is much larger than $1/\tau$, then the target must be within $c\tau/4$ (75 m for $\tau = 1$ μs) of the centre of the resolution volume to provide a significant contribution to the I and Q signal samples.

Table 2. *Calibration Coefficients for the antenna horns and corresponding receive channels of the horizontal array. All values correspond to a transmitted pulse width of 200 ns.*

f_t (GHZ)	HORN 1 CH. 9	HORN 2 CH. 10	HORN 3 CH. 11	HORN 4 CH. 12	HORN 5 CH. 13	HORN 6 CH. 14	HORN 7 CH. 15	HORN 8 CH. 16
8.9	0.0172	0.0206	0.00844	0.00972	0.0112	0.0143	0.0126	0.0122
9.0	0.0164	0.0182	0.0170	0.0197	0.0231	0.0243	0.0314	0.0180
9.1	0.0368	0.0249	0.0261	0.0219	0.0152	0.0127	0.0113	0.0236
9.2	0.0121	0.0128	0.0299	0.0381	0.0226	0.0113	0.0153	0.0105
9.3	0.0101	0.0108	0.0158	0.0206	0.0215	0.00889	0.00876	0.00764
9.4	0.0120	0.00904	0.0145	0.0212	0.0281	0.0139	0.0168	0.00945

Table 3. *Calibration Coefficients for the antenna horns and corresponding receive channels of the horizontal array. All values correspond to a transmitted pulse width of 1.0 μs.*

f_t (GHZ)	HORN 1 CH. 9	HORN 2 CH. 10	HORN 3 CH. 11	HORN 4 CH. 12	HORN 5 CH. 13	HORN 6 CH. 14	HORN 7 CH. 15	HORN 8 CH. 16
8.9	0.0132	0.0127	0.00827	0.00983	0.0125	0.0103	0.00796	0.00753
9.0	0.0133	0.0119	0.0149	0.0179	0.0178	0.0122	0.0124	0.0139
9.1	0.0196	0.0130	0.0160	0.0171	0.0168	0.0124	0.0103	0.0113
9.2	0.0111	0.0109	0.0112	0.0160	0.0102	0.00808	0.00918	0.00953
9.3	0.0102	0.00919	0.00701	0.0107	0.0122	0.00933	0.00699	0.00644
9.4	0.0119	0.00908	0.00834	0.0109	0.0118	0.00909	0.00809	0.00872

In this case, the receiver bandwidth is large compared to $1/\tau$, i.e., $B_6/\tau = 5$ where B_6 is the 6 dB receiver bandwidth (see Table 1). Thus, the calibration target must be located between 7.935 and 7.965 km since it simultaneously contributed backscattered power to the range bins centred at 7.89 and 8.01 km. Consequently, the maximum possible distance between the corner reflector and the range of maximum weight corresponding to the resolution volume centred at 7.95 km was 15 m.

The uncertainty in the position of the corner reflector with respect to the centre of the resolution volume will cause the calibration coefficient calculated using Eq. (1) to be overestimated. Since the exact propagation conditions that existed at the time of the measurements are not known, it would not be useful to attempt to adjust the calibration coefficient for the exact position of the corner reflector. However, the magnitude of the overestimation can be determined by examining the weighting applied by the antenna system and receiver to the radar resolution volume. That is, Eq. (1) can be more accurately written as

$$\frac{P_t G^2(\theta,\phi)\,\lambda^2 G_{sys}\,|W(r)|^2\,\sigma}{(4\pi)^3 r^4} = \frac{\omega}{n_c}\sum_{n=0}^{n_c-1}\left(I_n^2 + Q_n^2\right) \qquad (3)$$

Table 4. *Uncalibrated* $\overline{I^2 + Q^2}$ *values for the antenna horns and corresponding receive channels of the horizontal array. Each average was formed using 3700* I *and* Q *samples. The values are stated in units of Watts, assuming a system resistance of 1 Ω. The transmitted pulse width is 200 ns.*

f_t (GHZ)	HORN 1 CH. 9	HORN 2 CH. 10	HORN 3 CH. 11	HORN 4 CH. 12	HORN 5 CH. 13	HORN 6 CH. 14	HORN 7 CH. 15	HORN 8 CH. 16
8.9	0.6847	0.3475	0.5352	0.8265	0.4533	0.3557	0.4863	0.5436
9.0	0.7309	0.4011	0.2714	0.4154	0.2236	0.2123	0.1990	0.3748
9.1	0.3399	0.3047	0.1841	0.3890	0.3537	0.4226	0.5758	0.2984
9.2	1.0299	0.5915	0.1598	0.2228	0.2372	0.4742	0.4243	0.6677
9.3	1.2839	0.7292	0.3155	0.4286	0.2599	0.6284	0.7718	0.9548
9.4	1.0232	0.8293	0.3255	0.3971	0.1890	0.3820	0.3827	0.7335

Table 5. *Uncalibrated* $\overline{I^2 + Q^2}$ *values for the antenna horns and corresponding receive channels of the horizontal array. Each average was formed using 3700* I *and* Q *samples. The values are stated in units of Watts, assuming a system resistance of 1* Ω*. The transmitted pulse width is 1.0* μs*.*

f_t (GHZ)	HORN 1 CH. 9	HORN 2 CH. 10	HORN 3 CH. 11	HORN 4 CH. 12	HORN 5 CH. 13	HORN 6 CH. 14	HORN 7 CH. 15	HORN 8 CH. 16
8.9	0.8948	0.5641	0.5461	0.8172	0.4052	0.4932	0.7706	0.8792
9.0	0.8623	0.5841	0.2950	0.4356	0.2773	0.4043	0.4834	0.4651
9.1	0.6370	0.5826	0.2999	0.4997	0.3207	0.4328	0.6326	0.6242
9.2	1.0753	0.6611	0.4067	0.5084	0.5002	0.6332	0.6747	0.7011
9.3	1.1061	0.7473	0.6186	0.7178	0.3995	0.5215	0.8428	0.9859
9.4	0.9661	0.7704	0.5294	0.7191	0.4185	0.5446	0.7409	0.7416

where G^2 describes the two-way antenna system gain pattern and W describes the range weighting applied to the resolution volume. Assuming that the receiver transfer function can be approximated by a Gaussian function and that the transmitted pulse shape is rectangular, W can be written as

$$W(r) = \frac{1}{2}\left\{\operatorname{erf}\left[\left(\frac{\pi B_6}{c\sqrt{\ln 2}}\right)\left(r_c - r + \frac{c\tau}{4}\right)\right] - \operatorname{erf}\left[\left(\frac{\pi B_6}{c\sqrt{\ln 2}}\right)\left(r_c - r - \frac{c\tau}{4}\right)\right]\right\} \tag{4}$$

where r is the range to a point in the resolution volume, r_c is the range to the centre of the resolution volume, c is the speed of light, and erf is the error function (see Doviak and Zrnić [5], p 79). The antenna system two-way gain pattern, G^2, can be approximated by a Gaussian function at angles close to the beam axis, i.e.,

$$G^2(\theta,\phi) = G_b^2 \exp\left\{-8\ln 2\left[\left(\frac{\theta-\theta_c}{\theta_6}\right)^2 + \left(\frac{\phi-\phi_c}{\phi_6}\right)^2 \sin^2\theta\right]\right\} \tag{5}$$

where G_b is the antenna system gain on the beam axis, θ and ϕ are the polar and azimuth angles, respectively, of a point in the resolution volume, θ_c and ϕ_c are the polar and azimuth angles specifying the beam axis, θ_6 is the 6 dB beamwidth along the θ coordinate, and ϕ_6 is the 6 dB beamwidth along the ϕ coordinate.

The received power calculated using Eqs. (2), (3), (4), and (5) with r = 7.965 km, r_c = 7.95 km, θ = 90.077°, and θ_c = 90.0° is 0.035 dB less than that calculated using Eqs. (1) and (2) with r = 7.95 km. Therefore, the error in ω due to the unknown position of the corner reflector is expected to be near 0.035 dB or 0.81 %. This magnitude of error will have an insignificant effect on comparisons of EARS weather clutter measurements with simulated data.

3 Evaluation of the calibration coefficient

3.1 Weather clutter field trials

The weather clutter field trials of June 18-22, 1997 used a radiosonde and a Joss-Waldvogel disdrometer to characterize the environment. A photograph of the EARS site including these two instruments is shown in Figure 5. The environmental inputs required by the weather clutter simulation were derived from the data of these two instruments. The output of the simulation was then compared with the EARS data simultaneously measured using horn 4 and channel 12.

The specific case corresponding to the example calibration coefficient derived in Section 2.2 (i.e., $\omega = 1.79 \times 10^{-2}$; horn 4, channel 12) occurred in the afternoon of June 18, 1997 when a stratiform precipitation field passed over the DREO experiment site on the shore of the Ottawa River. At 14:00 local time a radiosonde was launched. Simultaneous EARS

Figure 5. *DREO experimental site located on the shore of the Ottawa River. EARS is inside the building marked "EARS". The insets show the radiosonde and the Joss-Waldvogel disdrometer, which was located on the trailer behind the EARS building.*

measurements were also made, using several different waveforms, along a horizontal ray over the river. The specific parameters describing the EARS measurements relevant to this case are shown in Table 1. The Joss-Waldvogel disdrometer made measurements throughout the entire time period of the field trials. In addition, volume scan data measured at 10 minute intervals by the Carp weather radar were purchased from Environment Canada. These scans consisted of 24 PPI's (Plan Position Indicator) of reflectivity factor measured at 24 elevations between 0.3° and 34.4° out to a range of 240 km.

The Joss-Waldvogel disdrometer provides data of the diameters and impact times of the raindrops landing on its sensor head. The reflectivity factor, Z, and rain rate, R, of the measured precipitation can be calculated from these data. The Joss-Waldvogel disdrometer was originally designed to determine these two quantities, and has been used for more than 30 years, by many researchers, for this purpose. The coefficients relating these two quantities in a power law are required inputs of the weather clutter simulation.

The reflectivity factor is essentially a measure of the backscatter cross section of the precipitation (see Doviak and Zrnić [5], p 82) and can be related to the power received by a radar using the weather radar equation. Thus, the disdrometer can provide an independent quantitative measure of the precipitation that can also be derived from the EARS data. Comparing the Z values derived from the two instruments provides a means of assessing the calculated calibration coefficient.

3.2 Derivation of Z and R from the disdrometer data

The first step in calculating Z and R from the disdrometer measurements was to divide the diameter data into sets. All of the data measured on June 18, 1997 are plotted in Figure 6 as drop diameter versus impact time. Each set of diameter data was defined by a contiguous time period in which the mean precipitation properties remained reasonably constant. The precipitation event observed on June 18, 1997 was divided into 34 such time periods. The start and end time of each period is listed in Table 6.

A histogram of raindrop diameters, $n_i(D_i)$, was then formed from the diameter data within each time period. This histogram describes the number of raindrops that were measured in each of 34 diameter bins that divide the size range of 0.25 to 5.3 mm. The centre and width of each diameter bin are given in Table 7. The raindrop size spectrum, $N_i(D_i)$, represents the number concentration of raindrops per diameter interval per unit volume. This quantity was calculated for each time period as

$$N_i = \frac{n_i}{T\, v_i\, A\, \Delta D_i} \tag{6}$$

where n_i is the number of raindrops having sizes within the i^{th} diameter bin, T is the time period over which the spectrum is calculated, A (= 50 cm^2) is the area of the sensing head, and ΔD_i is the width of the i^{th} bin. The terminal velocity, $v_i(D_i)$, corresponding to the centre of each diameter bin was calculated using the equations of Best [6] for diameter bins 1 and 2, i.e.,

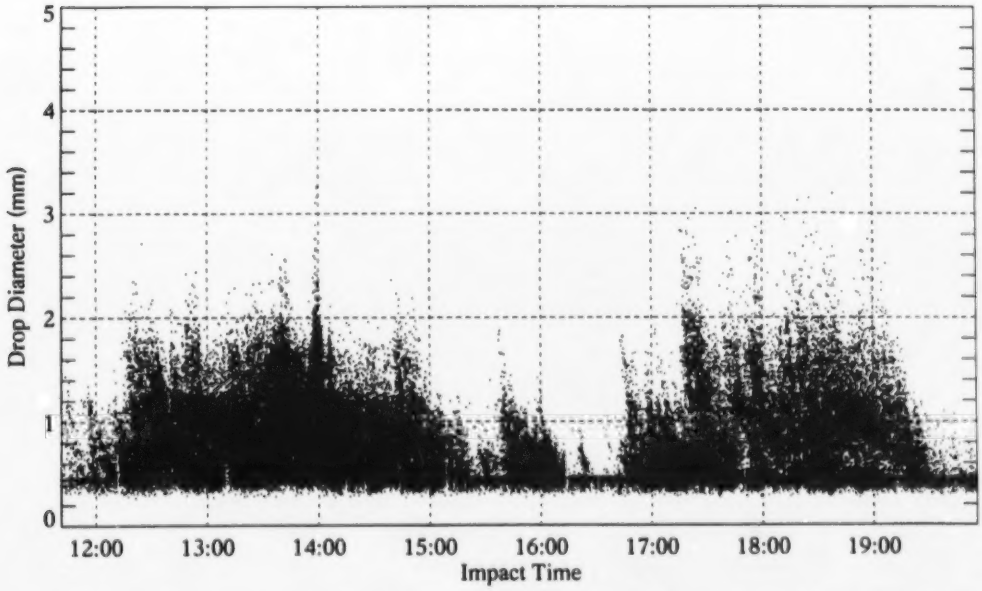

Figure 6. *Disdrometer data measured during the stratiform precipitation of June 18, 1997. Each dot represents an individual raindrop that impacted on the sensor head.*

$$v_i = 9.32\left\{\exp\left[-\left(\frac{D_i}{1.77}\right)^{1.147}\right]-1\right\} \tag{7}$$

where D_i is the diameter corresponding to the centre of the i^{th} bin. The Atlas et al. [7] parameterization of the Gunn and Kinzer [8] fall-speed data was used for the remaining diameter bins, i.e.,

$$v_i = 10.3\exp(-0.6D_i) - 9.65 \tag{8}$$

The units of D and v must be given in mm and m s^{-1}, respectively, in both Eqs. (7) and (8).

Assuming that the Rayleigh scattering approximation is valid, Z in mm^6 m^{-3} and R in mm h^{-1} were calculated from the raindrop size spectra as

$$Z = \sum_{i=1}^{34} N_i D_i^6 \Delta D_i \tag{9}$$

$$R = \frac{\pi}{6}\sum_{i=1}^{34} N_i D_i^3 v_i \Delta D_i \tag{10}$$

Table 6. Time periods defining the 34 sets of diameter data. Times are given in local time (eastern standard time).

SET	START TIME	END TIME	SET	START TIME	END TIME
1	11:41:20	11:54:11	18	14:54:44	15:08:23
2	11:54:11	12:11:48	19	15:13:02	15:20:41
3	12:11:48	12:31:13	20	15:20:41	15:35:11
4	12:31:13	12:39:17	21	15:35:11	15:41:45
5	12:39:17	12:47:54	22	15:41:45	16:13:18
6	12:47:54	12:57:04	23	16:19:35	16:26:17
7	12:57:04	13:09:28	24	16:42:26	17:15:05
8	13:11:07	13:20:49	25	17:15:05	17:28:21
9	13:20:49	13:33:41	26	17:28:21	17:38:11
10	13:33:41	13:47:37	27	17:38:11	18:00:00
11	13:47:37	13:56:06	28	18:00:00	18:15:29
12	13:56:06	14:04:16	29	18:15:29	18:40:06
13	14:04:16	14:14:24	30	18:40:06	18:50:46
14	14:14:24	14:19:44	31	18:50:46	19:09:36
15	14:19:44	14:24:47	32	19:09:36	19:18:46
16	14:24:47	14:37:38	33	19:18:46	19:32:02
17	14:40:06	14:54:44	34	19:32:02	19:56:14

3.3 Derivation of *Z* and *R* from the EARS data

The EARS Z values were determined from the I and Q data using a form of the radar equation that describes the power received from a volume of precipitation scatterers, i.e.,

$$P_r = \frac{\omega}{n_c}\sum_{n=0}^{n_c-1}\left(\mathrm{I}_n^2 + \mathrm{Q}_n^2\right) = \int_{\upsilon}\frac{P_t\,\lambda^2\,G_{sys}\,G^2\,|W|^2}{(4\pi)^3\,L_a\,r^4}\eta\,\mathrm{d}\upsilon \qquad (11)$$

where υ represents the radar resolution volume, and L_a is the two-way attenuation of the radar signal along the path from the antenna to the resolution volume. Again assuming that Rayleigh scattering applies, the reflectivity of the precipitation, η, can be related to Z as

$$\eta = \frac{\pi^5}{\lambda^4}\left|K_w^2\right|Z \qquad (12)$$

where $|K_w|^2$ is a function of the complex index of refraction of water. If it is further assumed that Z and L_a are constant within the resolution volume, Eq. (11) can be written as

Table 7. Diameter bins used to construct the raindrop size spectra.

BIN NUMBER	BIN CENTRE (mm)	BIN WIDTH (mm)	BIN NUMBER	BIN CENTRE (mm)	BIN WIDTH (mm)
1	0.3	0.1	18	2.025	0.15
2	0.4	0.1	19	2.2	0.2
3	0.5	0.1	20	2.4	0.2
4	0.6	0.1	21	2.6	0.2
5	0.7	0.1	22	2.8	0.2
6	0.8	0.1	23	3.0	0.2
7	0.9	0.1	24	3.2	0.2
8	1.0	0.1	25	3.4	0.2
9	1.1	0.1	26	3.6	0.2
10	1.2	0.1	27	3.8	0.2
11	1.3	0.1	28	4.0	0.2
12	1.4	0.1	29	4.2	0.2
13	1.5	0.1	30	4.4	0.2
14	1.6	0.1	31	4.6	0.2
15	1.7	0.1	32	4.8	0.2
16	1.8	0.1	33	5.0	0.2
17	1.9	0.1	34	5.2	0.2

$$Z = \frac{64 P_r \lambda^2 L_a}{P_t G_{sys} \pi^2 |K_w|^2} \left[\int_{r_1}^{r_2} \int_{\theta_1}^{\theta_2} \int_{\phi_1}^{\phi_2} \frac{G^2(\theta,\phi)|W(r)|^2}{r^2} \sin\theta \, dr \, d\theta \, d\phi \right]^{-1} \tag{13}$$

where Eq. (12) has been used to replace η, and the volume element, $d\upsilon$, has been expanded into spherical polar coordinates.

The limits of integration in Eq. (13) define the shape of the resolution volume. The value of the triple integral will approach an asymptote as these limits are increased toward infinity. The integration limits were determined by solving the following equation for r, θ, and ϕ.

$$\frac{G^2(\theta,\phi)|W(r)|^2}{r^2} = \frac{\alpha G^2(\theta_c,\phi_c)|W(r_c)|^2}{r_c^2} \tag{14}$$

The value of α was set to 1.0×10^{-9}. This allowed the limits of integration to be determined such that the calculated value of the triple integral was correct to within the limits of double precision numbers.

The limits, r_1 and r_2, were determined along the beam axis by setting $\theta = \theta_c$ and $\phi = \phi_c$ in the left side of Eq. (14), which gave

$$\frac{W^2(r)}{r^2} = \frac{\alpha W^2(r_c)}{r_c^2} \tag{15}$$

If W is described using Eq. (4) then Eq. (15) represents a transcendental equation having two solutions, $r = r_1$ and $r = r_2$. These two solutions were determined by numerically solving Eqs. (4) and (15).

The limits, $\theta_1(r)$ and $\theta_2(r)$, were determined by first solving Eq. (14) for θ with $\phi = \phi_c$ and G^2 determined by Eq. (5), i.e.,

$$\begin{aligned} \theta_1(r) &= \theta_c - \left\{ \frac{-\theta_6^2}{8 \ln 2} \ln \left[\frac{\alpha W^2(r_c) r^2}{W^2(r) r_c^2} \right] \right\}^{\frac{1}{2}} \\ \theta_2(r) &= \theta_c + \left\{ \frac{-\theta_6^2}{8 \ln 2} \ln \left[\frac{\alpha W^2(r_c) r^2}{W^2(r) r_c^2} \right] \right\}^{\frac{1}{2}} \end{aligned} \tag{16}$$

An additional constraint is placed on θ_2 to account for the truncation of the measurement volume by the surface of the river. Using the law of triangles, the polar angle, θ_s, of a point at range r on the surface of the river can be written as

$$\theta_s(r) = \cos^{-1} \left[\frac{R_e^2 - r^2 - (R_e - h_a)^2}{2r(R_e + h_a)} \right] \tag{17}$$

where R_e is the radius of the earth, and h_a is the height of the antenna above the river. Thus, the θ_2 limit is taken as $\theta_s(r)$ at all points where $\theta_s(r)$ is less than $\theta_2(r)$ as given by Eq. (16).

The limits $\phi_1(r, \theta)$ and $\phi_2(r, \theta)$ were determined by solving Eq. (14) for ϕ, i.e,

$$\begin{aligned} \phi_1(r, \theta) &= \phi_c - \left(\frac{\phi_6^2}{\sin^2 \theta} \left\{ -\frac{1}{8 \ln 2} \ln \left[\frac{\alpha W^2(r_c) r^2}{W^2(r) r_c^2} \right] - \left[\frac{\theta - \theta_c}{\theta_6} \right]^2 \right\} \right)^{\frac{1}{2}} \\ \phi_2(r, \theta) &= \phi_c + \left(\frac{\phi_6^2}{\sin^2 \theta} \left\{ -\frac{1}{8 \ln 2} \ln \left[\frac{\alpha W^2(r_c) r^2}{W^2(r) r_c^2} \right] - \left[\frac{\theta - \theta_c}{\theta_6} \right]^2 \right\} \right)^{\frac{1}{2}} \end{aligned} \tag{18}$$

Once the limits were determined the triple integral of Eq. (13) was evaluated numerically for each range bin.

The Z calculation in Eq. (13) is a function of the attenuation, L_a. However, L_a is a function of the spatial distribution of Z, or equivalently of R, which are both initially unknown. Consequently, Z and L_a were determined through an iterative process. An initial estimate for Z was calculated by setting $L_a = 1$ in Eq. (13) for all range bins. An initial estimate of R at each range bin was then determined from a disdrometer determined power law relating Z and R (see Eq. (19) below). An estimate of L_a as a function of range was then calculated from the initial R estimate using the same empirical relations that are used in the weather clutter simulation (see Thomson [1], p 30). This initial L_a estimate was then used in Eq. (13) to recalculate Z as a function of range. This new range profile of Z was used to recalculate R, which was used to recalculate L_a, which in turn was used to again recalculate Z. This process was continued until the Z values converged. The Z values were then smoothed with a running average to reduce statistical fluctuations. This gave the final Z values that were compared with the disdrometer Z values. The final R values corresponding to the EARS measurements were then calculated from these final Z values using the disdrometer determined power law.

The Z-R power law was determined by performing a linear regression in a log-log space on the 34 (Z, R) data points calculated using Eqs. (9) and (10) (see Figure 7). The parameters of the best-fit line (correlation coefficient 0.952) define a power law relationship between Z in $mm^6\ m^{-3}$ and R in $mm\ h^{-1}$, i.e.,

$$Z = 239 R^{1.37} \tag{19}$$

The parameters of this power law relationship are required inputs of the weather clutter simulation. The specific numbers 239 and 1.37 were used to characterize the rain field

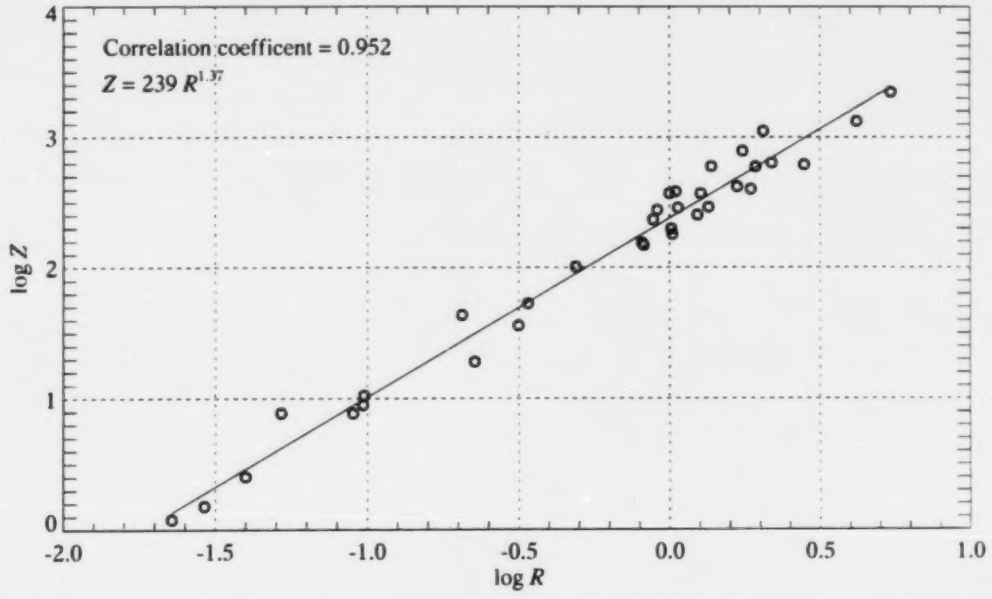

Figure 7. *Relationship between disdrometer derived Z and R. The Z-R relation is valid for the period 11:41:20 to 19:56:14 local time on June 18, 1997.*

everywhere within the viewing volume of the radar for the entire precipitation event of June 18, 1997.

3.4 Comparison of EARS and disdrometer data

Perfect agreement between the Z values determined from disdrometer data and from EARS data can not be expected in general because of the vastly different measurement volumes and times scales associated with the two measurement techniques. For example, the EARS range bin closest to the disdrometer, i.e., at $r = 1$ km, had a 6 dB resolution volume of $\sim 2.4 \times 10^7$ m^3 and an approximately ellipsoidal shape. The time required for EARS to measure the average received power in this range bin was only 64 ms (see Table 1). The volume of raindrops sampled by the disdrometer is a narrow cylinder above the sensing head that curves with increasing height. The curvature of the cylinder is caused by the horizontal motion of raindrops through a wind field containing vertical wind shear. The size of the measurement volume is dependent upon the raindrop fall speeds, which are a function of the raindrop sizes. It is also dependent upon the measurement time. The longest measurement time used on June 18, 1997 was 1959 s (see set 24 of Table 6). Thus, for the largest sized drops, ~ 3.2 mm in this case, the disdrometer measurement volume was ~ 80 m^3, which is 5 orders of magnitude smaller than the EARS volume. However, if EARS and the disdrometer are properly calibrated then they should measure approximately the same value of Z.

The disdrometer Z values, and the corresponding R values, as determined through the process described in Section 3.2, are plotted as a function of time in the top of Figure 8. The data

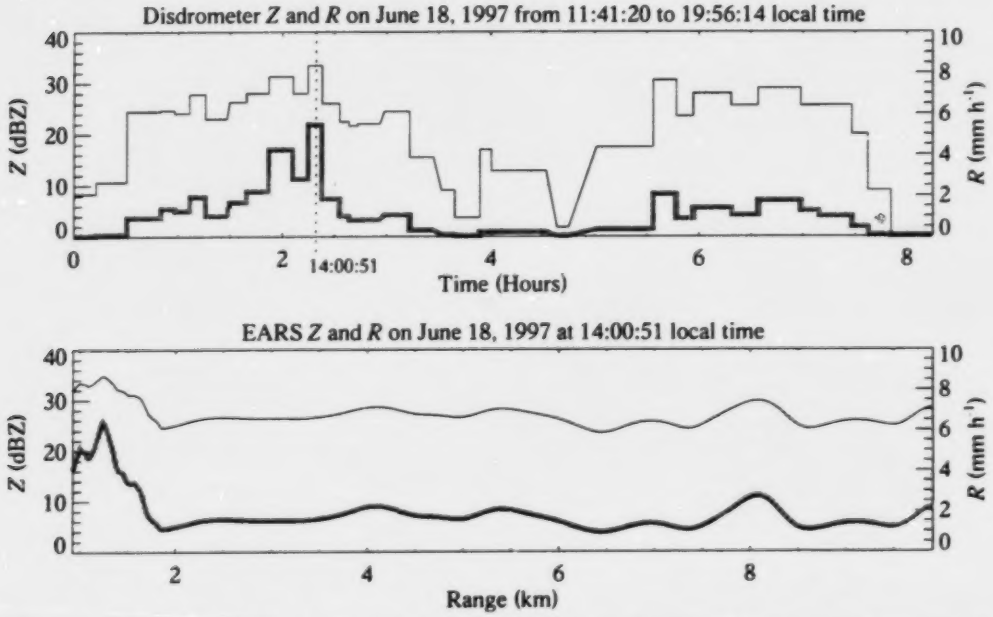
Disdrometer Z and R on June 18, 1997 from 11:41:20 to 19:56:14 local time
Z (dBZ)
R (mm h-1)
14:00:51
Time (Hours)
EARS Z and R on June 18, 1997 at 14:00:51 local time
Z (dBZ)
R (mm h-1)
Range (km)

Figure 8. *Comparison of reflectivity factor, Z, and rain rate, R, as determined from measurements made by EARS and the collocated Joss-Waldvogel disdrometer. The Z data are shown with thin black lines and the R data are shown with thick grey lines. The vertical dashed line in the upper plot marks the time of the EARS measurements.*

show a variation from 0.4 (almost no rain at all) to 33.5 dBZ (5.47 mm h^{-1}). This range is consistent with the measurements made by the Carp radar.

Figure 9 shows a large scale horizontal cross section through the Carp radar *Z* data at an altitude of 1.5 km. The corresponding volume scan data were measured during 13:55 - 14:00 local time. The cross section shows areas of no precipitation and also precipitation areas having *Z* values up to a maximum of 37 dBZ. The location of EARS and the disdrometer is marked with a red cross.

Unfortunately, most of the *Z* values measured by the Carp radar in the lowest levels at short

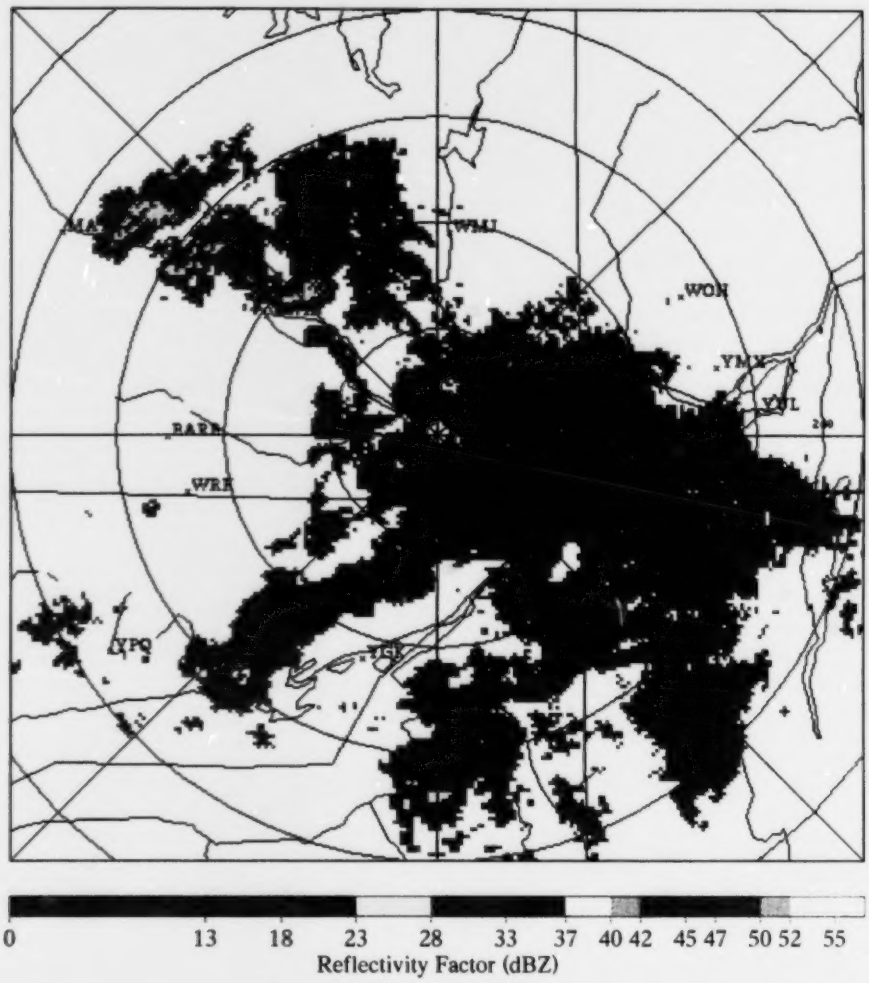

Figure 9. *Horizontal cross section through the Carp radar data at 1.5 km altitude. The volume scan data were measured during the 5 minute period prior to 14:00 local time on June 18, 1997. The red cross marks the location of EARS and the disdrometer on the Ottawa river. Range rings are drawn at 60 km intervals.*

ranges were not recorded. This was due to a limitation on the data transfer rate between the Carp radar and the Environment Canada archiving site. This region of no data included the location of the disdrometer and EARS. However, a significant amount of data was recorded in the lowest levels at longer ranges. A histogram of Z for all available measurements below 1 km altitude, excluding those contaminated by ground clutter, is shown in Figure 10. This plot shows that the Carp radar Z values ranged from 0 to 31 dBZ, which is in reasonable agreement with the range of Z values measured by the disdrometer. Although these data can not be directly compared, both the Carp radar and the disdrometer data sets are representative of the precipitation occuring on June 18, 1997. The agreement between the magnitudes of the two sets provides confidence in the accuracy of the disdrometer measurements.

The EARS Z values, and the corresponding R values, as determined through the process described in Section 3.3 are plotted as a function of range in the bottom of Figure 8. The vertical dashed line in the upper plot indicates that the EARS measurements were made at the time of the most intense rainfall observed by the disdrometer. At this time the disdrometer derived Z value was 33.5 dBZ. The Z values derived from EARS data ranged from 23.0 dBZ to 34.7 dBZ, with the higher values corresponding to the ranges (~ 1 km) that were closest to the disdrometer. Thus, the Z values derived from the EARS data at the closest possible range to the disdrometer are in agreement with the value determined from the disdrometer data. The EARS Z values are also consistent with those measured by the Carp radar. These comparisons indicate that channel 12 has been effectively calibrated. Since the same method of calibration has been applied to all channels of the horizontal receive array, the favourable comparison above also indicates that the entire horizontal array has been effectively calibrated.

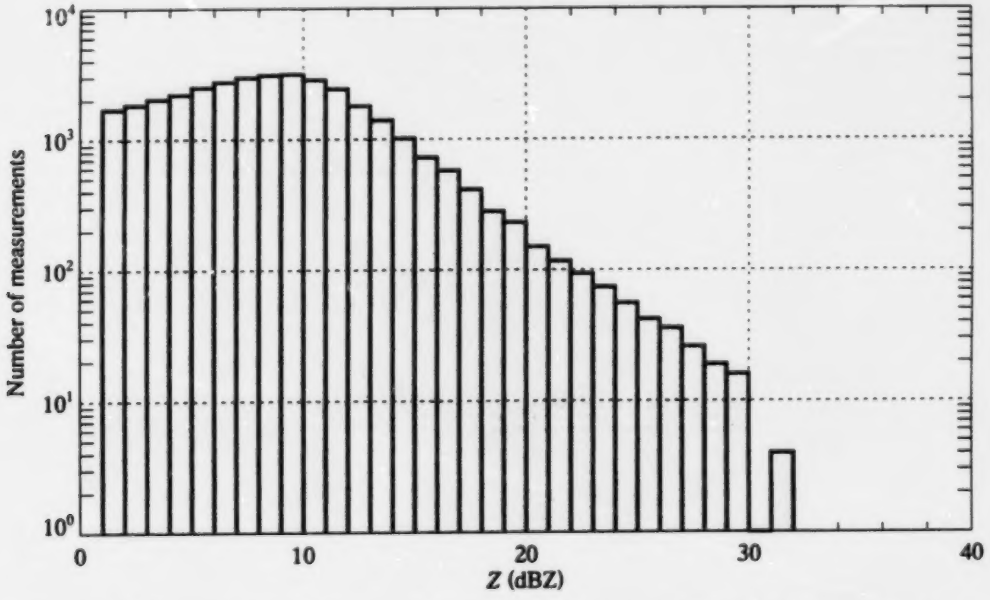

***Figure 10.** Histogram of the Carp radar Z values measured below 1 km altitude between 13:55 and 14:00 local time on June 18, 1997. Regions containing ground clutter have been omitted from the calculation.*

4 Summary and conclusions

This report has presented the method used to calculate calibration coefficients that properly scale the mean power represented by the in-phase, I, and quadrature, Q, signal samples measured by the elements of the horizontal receive array of the Experimental Array Radar System (EARS). A calibration coefficient, ω, corresponding to a particular antenna horn, receive channel, and transmitted waveform, was determined as the ratio of the expected power returned from a calibration target of known cross section to the average power of the I and Q signal samples actually measured by the given channel. Calibration coefficients for all 8 horns of the horizontal array were calculated for 6 transmitted frequencies and 2 pulse widths. An assessment was also made of the error in ω due to the uncertainty in the position of the calibration target. The value of ω corresponding to horn 4 of the EARS horizontal array (receive channel 12) and the transmitted waveform specified in Table 1 was found to be 1.79×10^{-2}. This value was required for the calibration of data measured during field trials designed to assess the accuracy of a high fidelity weather clutter simulation (Thomson [1]; Thomson and Riseborough [2]).

The accuracy of the example calibration coefficient (1.79×10^{-2}) was assessed by comparing reflectivity factor, Z, and rain rate, R, values derived from EARS measurements with those derived from simultaneous disdrometer measurements. These measurements were made for the purpose of evaluating the weather clutter simulation and only later were discovered to be useful for evaluating the calibration coefficient. Consequently, the conditions of comparison are not as good as they could be. For instance, the EARS and disdrometer measurements were not made at exactly the same location. However, differences in the derived values would be expected even if the measurement volumes of the two instruments were collocated since the temporal and spatial scales corresponding to the different measurement techniques are not the same. Regardless, similar values of Z and R were derived from the data of both instruments, and these values were within the range measured by the Carp weather radar. Thus, the horizontal receive array of EARS has been effectively calibrated.

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List of symbols/abbreviations/acronyms/initialisms

EARS	Experimental Array Radar System
DREO	Defence Research Establishment Ottawa

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Calibration coefficients have been calculated for the horizontal receive array of the Experimental Array Radar System (EARS). These coefficients scale the power produced at the output of a receive channel to the power expected based on physical considerations. In total 96 coefficients have been calculated for the 8 antenna horns and their respective receive channels. Each horn/channel was calibrated for 12 transmitted waveforms corresponding to the different combinations of 6 frequencies and 2 pulse widths. The method of calibration is described using the example case of antenna horn 4 (receive channel 12), a transmitted frequency of 9.0 GHz, and a pulse width of 1.0 μs. Calibrated data corresponding to this case were required to evaluate a high fidelity radar weather clutter simulation developed at the Defence Research Establishment Ottawa (DREO). The accuracy of the example calibration coefficient (1.79×10^{-2}) was evaluated by comparing the reflectivity factor and rain rate derived from EARS measurements of precipitation with similar values derived from simultaneous measurements made by a Joss-Waldvogel disdrometer. The results of the comparison indicated that the horizontal receive array of EARS has been effectively calibrated.

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radar, calibration, corner reflector, weather clutter, rain